Nitrogen Effects on Onion Yield Under Drip and Furrow Irrigation

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ABSTRACT

Onion (*Allium cepa* L.) is a high cash value crop with a very shallow root system that is frequently irrigated and fertilized with high N rates to maximize yield. Converting from furrow-irrigated to drip-irrigated onion production may reduce N fertilizer needs, water inputs, and NO_3–N leaching potential. Onion growth and N uptake, fresh yield, and residual soil NO_3–N were determined under drip and furrow irrigation on a clay loam soil with N fertilizer rates from 0 to 224 kg N ha^{-1}. Onions were sampled bi-weekly from 25 May to 30 August in 2005 and 2006 from each treatment. In 2005, 72% less water was applied with the drip system compared with furrow system, and 57% less in 2006. Onion yields were significantly greater with the drip system. Total marketable fresh onion yield increased with increasing N rate in 2005 only. The drip system had more colossal and jumbo sized onions and less medium sized onions than the furrow system. Biomass production and N accumulation accelerated in mid-June each year with an average total N accumulation (leaves + bulbs) of 121 kg N ha^{-1} at final harvest. Irrigation water use efficiency (IWUE) and N use efficiency (NUE) were higher with the drip system than with the furrow system. Residual soil NO_3–N levels were greater in the drip-irrigated treatments after onion harvest in 2005 than in the furrow-irrigated treatments, but soil NO_3–N levels were similar after harvest in 2006. Adjusted gross economic returns (less the cost of N, water, and drip system) were greater with drip irrigation than with furrow irrigation. This study demonstrates that fresh onion yields, potential economic returns, IWUE, and NUE can be improved in Colorado by using drip irrigation for onion production rather than furrow irrigation.

High NO_3–N and salinity levels have been reported in groundwater in the Arkansas River Valley in Colorado (Austin, 1997; Ceplecha et al., 2004, Gates et al., 2006), which is a major production area for onion and other vegetable crops in rotation with alfalfa (*Medicago sativa* L.), corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), winter wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L.). High rates of N fertilizer (>200 kg N ha^{-1}) are usually applied to onion in the western United States to increase overall yield and bulb size, generally without regard to soil testing (Bartolo et al., 1997, Brown, 1997, 2000; Drost et al., 1997; Stevens, 1997). Halvorson et al. (2002) reported N fertilizer use efficiency (NFUE) by onion to be about 15%. Sammis (1997) also reported the need for high rates of N on onion to optimize yield in New Mexico, but expressed concern about leaching of NO_3–N from the root zone and the low NFUE (30%) by onion. Onion has a shallow rooting depth (<60 cm) and requires frequent irrigation to maintain market grade and quality (Schwartz and Bartolo, 1995). High N fertilization rates, shallow water tables, and frequent irrigation to establish and maintain an onion crop all contribute to a high NO_3–N leaching potential (Ells et al., 1993).

Sullivan et al. (2001) and Brown (2000) developed nutrient management plans for onion production in the Pacific Northwest to help reduce N application rates, to improve NUE, and to minimize the detrimental effects of fertilizer N on groundwater. Schwartz and Bartolo (1995) developed similar nutrient management guidelines for Colorado. Bartolo et al. (1997) and Brown (1997) point out that N fertilization costs are generally <2% of onion production costs, therefore, growers are not very concerned about N application rate, other than ensuring that sufficient N is present. Although these N fertilizer management guidelines recommend limiting N application when soil N is high, growers often apply N to ensure high yields and large sized onions. Irrigation, crop, and N management practices need to be developed to reduce NO_3–N leaching potential and improve NUE in Colorado (Halvorson et al., 2002, 2005).

Gates et al. (2006) reported the need to use more efficient irrigation methods in the Arkansas River Valley in Colorado to lower the levels of the groundwater table to reduce the impact of salinity on crop yields. They recommended converting to sprinkler and drip irrigations systems that required less water application to avoid excessive water movement below the crop root zone. Converting from furrow to drip irrigation has potential for reducing the amount of irrigation water needed to produce a high yielding onion crop (Sammis, 1980;

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Abbreviations: AN, available N [soil N (0–60 cm depth) + fertilizer N added + irrigation water N]; AVRC, Arkansas Valley Research Center; ET, evapotranspiration; IWUE, irrigation water use efficiency; NFUE, N fertilizer use efficiency; NUE_1, nitrogen use efficiency based on N uptake; NUE_2, nitrogen use efficiency based on fresh onion yield.

Shock et al., 2007). A more uniform application of water can be achieved with drip irrigation with little or no water runoff, deep percolation, evaporation, and water contact with onion leaves, which reduces disease potential (Shock, 2006; Shock et al., 2004, 2007).

Following onion planting in the semiarid Arkansas River Valley in southeastern Colorado, frequent irrigation is needed to achieve germination and keep the young seedlings alive. Drip irrigation has the potential to apply water frequently and uniformly to the onion seed row on an onion bed without wetting the soil between onion beds (Shock et al., 2007). Furrow irrigation requires that sufficient water be applied to wet the furrow area plus the onion bed, which requires more water than a drip system. With the furrow system and frequent irrigation, there is greater potential for NO_3–N leaching and excess water contribution to the shallow groundwater table which contributes to the soil salinity problems in the Arkansas River Valley in Colorado (Gates et al., 2006). Converting to more efficient irrigation systems, such as drip irrigation for high cash value crops is one way to reduce excess water application above consumptive use of the crop and reduce NO_3–N leaching potential (Trout and Kincaid, 2007; Shock et al., 2004).

The objectives of the research reported here were to: (i) determine N fertilizer requirements of onion under drip and furrow irrigation in the Arkansas River Valley of Colorado to optimize yield and bulb size and (ii) evaluate the influence of N fertilizer rate and irrigation system on residual soil NO_3–N.

MATERIALS AND METHODS

This study was conducted on a Rocky Ford clay loam soil (fine-silty, mixed, calcareous, mesic Ustic Torriorthents) at the Arkansas Valley Research Center (AVRC) (38° 2′23′′ N, 103° 41′43′′ W), near Rocky Ford, CO. The soil had a pH of 7.6, soil organic matter content of 21 g kg^{-1}, soil electrical conductivity of 0.7 dS m^{-1}, sodium bicarbonate extractable P content of 17 mg kg^{-1}, ammonium acetate extractable K content of 296 mg kg^{-1}, and a clay and silt content of 410 and 290 g/kg soil in the 0- to 15-cm depth. Depth to water table at the AVRC ranges from 4.5 to 6 m.

In 2000, a N source and rate study was initiated under conventional till (disk, moldboard plow, roller harrow, landplane, etc. for seedbed preparation) and furrow-irrigated corn production practices (Halvorson et al., 2005). The same plot area and established N plots were used for the 2005 onion study, with modified N rates. The plot area had previously been in continuous corn for 4 yr (2000–2003) and chile pepper in 2004. The 2006 study was located in an adjacent field that had been cropped to soybean the previous year with no N fertilizer applied. Six N rates (0, 45, 90, 134, 179, and 224 kg N ha^{-1} or N1, N2, N3, N4, N5, N6 treatments, respectively) were established on 22 February in 2005 and 2006. Drost et al. (2002) demonstrated the benefit of using a polymer-coated urea for onion production; therefore, a polymer-coated urea was used in this study to reduce NO_3–N leaching during the early growth period when frequent irrigation is required to keep the onions healthy. The N source used in this study was a controlled-release polymer-coated urea (Duration Type III produced by Agrium Inc., Calgary, AB; cost of \$2.43 kg^{-1} N)[1] with a 90 to 120 d 80% release period in water at 23°C. The N fertilizer was broadcast on 22 February and incorporated with a harrow within a few days after application both years.

Two irrigation systems were used, furrow irrigation with 3.2 cm diam. siphon tubes, common practice in the Arkansas Valley, and drip irrigation (T-Tape: TSX-708–30–340, T-Systems, San Diego, CA)[1] with 30 cm between emitters and a flow rate of 1.1 L h^{-1}. The drip tape was located about 5- to 8-cm below the soil surface near the center of the bed between the two onion rows. The experimental design was a split-plot, randomized complete block with N rate as main plots (7.6 by 15.2 m) and irrigation system as subplots (3.8 by 15.2 m) in 2005 and 9.1 by 15.2 m main plots and 4.6 by 15.2 m subplots in 2006 with four replications.

Phosphorus fertilizer (0–46–0) was applied over the entire plot area at a rate of 112 kg P ha^{-1} before fall plowing. In the spring, the field was roller-harrowed, leveled, and bedded before N application. Following N application the field was cultivated to incorporate the N fertilizer and rebedded for onion planting.

Onion (var. Ranchero, Nunhems USA, Inc., Parma, ID[1]) were planted on 8 March in 2005 and 2006 at a seeding rate of about 320,000 seeds ha^{-1}. At harvest, the plant population was 263,423 plants ha^{-1} in 2005 and 310,763 plants ha^{-1} in 2006 when averaged over all plots. Two rows of onion spaced 25 cm apart were planted in the center of 76 cm wide beds. The onions were harvested on 30 August both years for fresh weight yield and graded for size. Marketable onion sizes (Schwartz and Bartolo, 1995) were colossal (>10.2 cm diam.), jumbo (7.6–10.2 cm diam.), and medium (5.1–7.6 cm diam.). Final onion harvest yields are expressed as fresh onion weight ha^{-1} with an average water content of 918 g kg^{-1}. Estimated gross return per hectare was calculated based on a harvest price of \$441 Mg^{-1} of colossal, \$353 Mg^{-1} of jumbo, and \$265 Mg^{-1} of medium size onions in 2005 and \$617 Mg^{-1} of colossal, \$529 Mg^{-1} of jumbo, and \$352 Mg^{-1} of medium size onions in 2006. Water cost was estimated at \$0.36 cm^{-1}. The drip irrigation system was estimated to cost \$1853 ha^{-1} (disposable drip tube used plus amortized cost for pump, filter, and set-up material used for more than 1 yr). Labor costs, although different for each irrigation system, were not considered in this simple economic analysis as well as other input costs (seed, herbicides, machinery, cultivation, etc.) which were the same for both irrigation systems. Herbicides were applied for weed control, with the plots being relatively weed free during the study period.

Soil water in the onion row was monitored almost daily during the early part of the onion growing season using Watermark[1] soil moisture sensors (Irrometer Company, Riverside, CA[1]) placed in the seed row at a depth of 20 cm, and by the "feel" method (Klocke and Fischbach, 1998) for each of the irrigation systems. Soil water tension was maintained at about –20 kPa (Shock et al., 2007) in the drip-irrigated plots, but was more variable in the furrow-irrigated plots (–20 to –30 kPa) due to less frequent irrigations. The onions under drip irrigation were irrigated 20 times during the growing season with a total gross water application of 68.6 cm in 2005, and 17 times during the growing season in 2006 with a total gross

[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA, Agricultural Research Service.

water application of 87.9 cm. Onions under furrow irrigation received a total gross water application of 243.8 cm using 13 irrigations in 2005, and 202.7 cm in 2006 using 12 irrigations. Under furrow irrigation, water was applied to every furrow (76 cm spacing) to obtain uniform wetting of both onion rows on the bed. The runoff water from the furrow irrigated plots was estimated using a flume placed in the furrow at the lower end of the field. Approximately 82.3 cm of the water applied ran off the end of the field in the furrow irrigated system in 2005 and 62.0 cm in 2006. No water was lost off the end of the field with the drip system. Using the daily evapotranspiration (ET) value for onion obtained from the Colorado State University CoAgMet weather station located at AVRC, a estimated growing season ET was calculated for 2005 and 2006 with respective ET values of 74.2 and 78.2 cm. Water lost to deep percolation within the field was estimated by subtracting crop ET from precipitation received plus net irrigation water applied for the growing season. In 2005, an estimated 104 cm of water moved below the onion root zone with furrow irrigation and 11 cm with drip irrigation. In 2006, an estimated 88 cm of water was lost to deep percolation with the furrow irrigation and 36 cm with drip irrigation.

The average NO_3–N level in the irrigation water for the season was 1.4 mg kg^{-1}, with about 9.6 kg NO_3–N ha^{-1} added to the soil with the drip system and 22.6 kg NO_3–N ha^{-1} with the furrow irrigation system in 2005. The average NO_3–N level in the irrigation water for the season was 1.3 mg kg^{-1}, with about 11.4 kg NO_3–N ha^{-1} added to the soil with the drip system and 18.3 kg NO_3–N ha^{-1} with the furrow irrigation system in 2006 based on the net amount of irrigation water that stayed in the field.

Precipitation during the growing season in 2005 was 39.4 mm in March, 19.1 mm in April, 12.4 mm in May, 26.7 mm in June, 11.4 mm in July, and 55.1 mm in August and in 2006, 23.1 mm in March, 7.9 mm in April, 40.1 mm in May, 7.11 mm in June, 82.6 mm in July, and 96.8 mm in August. Total precipitation for the growing season (March–August) was 164 mm in 2005, a rather dry season during April, May, June, and July, and 258 mm in 2006, with March, April, May, and June being relatively dry.

Onion samples (six adjacent onions from each treatment) were collected at 2-wk intervals from 25 May until harvest (30 August) both years. At final harvest, two rows 3-m long were hand harvested from each plot. The onions at each sampling were separated into leaves and bulbs for dry matter and N-uptake determination. The onion parts were dried at 60°C to determine dry matter yield. Plant samples collected for N analysis were ground to pass a 150-μ screen and analyzed for N content using an Elementar vario Macro C-N analyzer (Elementar Americas, Inc., Mt. Laurel, NJ)[1].

Irrigation water use efficiency was calculated for each treatment. The IWUE was calculated as the fresh onion yield divided by the centimeter of net irrigation water applied. The NUE was expressed in two ways: (i) NUE_1 was equal to total N uptake (leaves + bulbs) divided by available N (AN) [soil N (0–60 cm) + fertilizer N + irrigation water N] times 100 and (ii) NUE_2 was equal to the fresh onion yield divided by AN. A NFUE was calculated for the 2006 onion crop because the whole plot area had been uniformly cropped with no variable N fertilizer treatments for several years before initiation of the study and the check (zero fertilizer N) plots represented a true zero fertilizer N treatment. The NFUE was calculated as follows:

$$\text{NFUE} = (\text{N uptake of fertilized treatment} - \text{N uptake of check plot}) \times 100/\text{N fertilizer rate.}$$

A NFUE value was not calculated for the 2005 onion crop because the check plots had not received N for more than 5 yr, compared with the fertilizer N plots in the study that had received N fertilizer each crop year. Thus the amount of mineralizable soil N was assumed to be less in the check plots (502 kg N ha^{-1} removed by previous crops from 2000 through 2004) than the other plots in the study receiving annual N fertilizer additions, therefore, a NUE was calculated as done by Halvorson et al. (2005) for the 2005 onion N treatments.

Soil NO_3–N levels in the 0- to 180-cm profile were measured before fertilization and after onion harvest. One soil core was collected with a hydraulic soil sampler from near the center of each plot each spring (0- to180-cm profile) before fertilization and planting and from the harvested onion row near the center of each plot after harvest each year. The soil core was sectioned into 15-cm increments for the first 30-cm depth, then into 30-cm increments to a depth of 180 cm for determination of NO_3–N content. Soil samples were sieved through a 2 mm screen in preparation for soil NO_3–N content determination. Soil NO_3–N concentrations (cadmium reduction) were determined by using a continuous flow analyzer (Lachat QuickChem FIA+8000 Series[1], Lachat Instruments, Loveland, CO) after extraction with 1 *M* KCl (soil to solution ratio, 1:5). A soil bulk density of 1.44 g cm^{-3} was used to convert soil NO_3–N to a mass basis.

Analyses of variance were performed using Analytical Software Statistix8 program (Analytical Software, Tallahassee, FL[1]) to determine treatment effects. All statistical comparisons were made at $\alpha = 0.05$ probability level unless otherwise stated using the least significant difference method for mean separation. A linear-plateau model was used to describe the yield and economic response of onions to N fertilization in 2005 using PROC NLIN in SAS (SAS Institute, 2002). If the analysis of variance indicated a significant F value for N rate, a linear or quadratic function was fit to the N response data using regression functions present in the graphics program SigmaPlot v. 8.0 (SPSS Inc., Chicago, IL).[1]

RESULTS

Onion Yield—Fresh Weight

Excellent marketable onion yields were obtained in 2005 (92.7 Mg ha^{-1}) and in 2006 (79.1 Mg ha^{-1}) with the 2005 marketable onion yield being significantly greater than the 2006 yield. Averaged over N rates and both years, the drip irrigation system produced significantly greater onion yield (91.9 Mg ha^{-1}) than the furrow irrigation system (79.9 Mg ha^{-1}). A significant ($P = 0.088$) N rate by year interaction was present due to an onion yield response to N fertilization in 2005 following chile pepper, but no response to N application in 2006 follow-

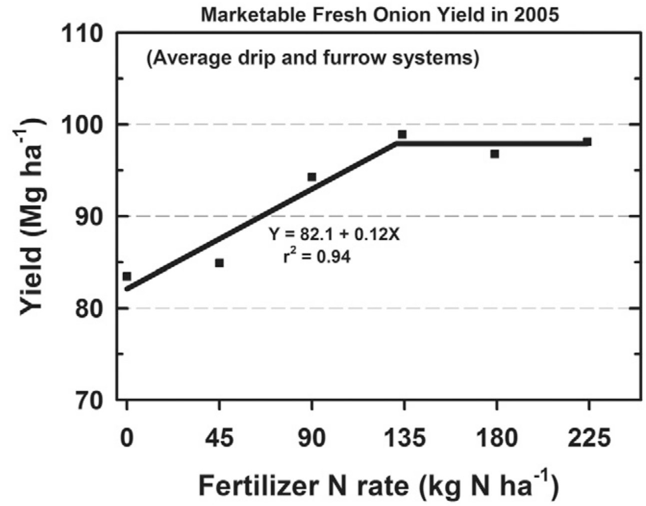

Fig. 1. Total marketable fresh onion yield in 2005 as a function of fertilizer N applied at Rocky Ford, CO, as described by a linear-plateau model.

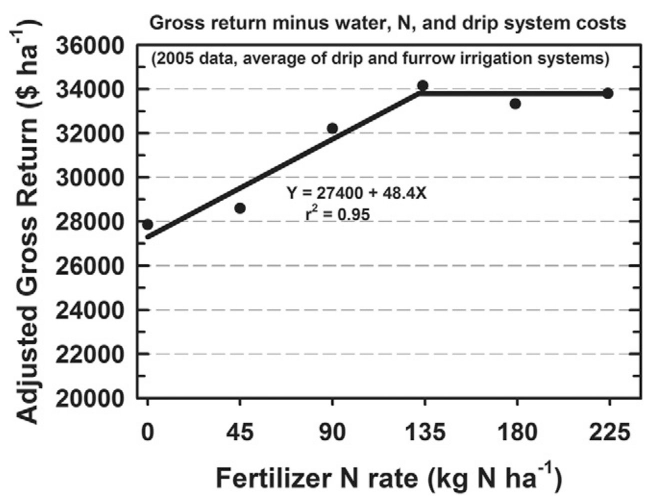

Fig. 2. Adjusted gross income as a function of fertilizer N rate in 2005, when averaged over irrigation systems at Rocky Ford, CO, as described by a linear-plateau model.

ing soybean (Fig. 1, Table 1). In 2005, onion yields were approaching maximum with an estimated N rate of 131 kg N ha^{-1} (Fig. 1). The response to N fertilization in 2005 probably resulted because of the prior conservative N management used for corn (2001–2003; Halvorson et al., 2005) and chile pepper (2004) production on the plot area. This probably resulted in removal of a sizeable amount of mineralizable N (502 kg N ha^{-1} from check plot) from the 2005 plots, making this a more responsive site to N fertilizer additions. In 2006, the onion plots were located on a field that had been in soybean in 2005 and well-fertilized corn for several years before soybean. Thus, the soil mineralizable N pool was probably larger in the 2006 plot area due to past N management, resulting in little response of onion to N fertilization in 2006. The lack of response of onion to N fertilization in 2006 was typical of previous unpublished N studies on onion by the authors at this location. The 2006 results suggest that onion producers can take a conservative approach to N application on onion in the Arkansas River Valley area of Colorado when following soybean or other legume crops in rotation. The 2005 onion study also indicates that N fertilizer rates of less than 150 kg N ha^{-1} can result in optimum onion yields, compared to the usual 200+ kg N ha^{-1} rates used by many producers.

Because of the significant N rate × year interaction for fresh onion yield, each year was analyzed separately when evaluating the influence of N rate on onion size. The quantity of colossal size onions ($P = 0.12$) and jumbo size onions ($P = 0.02$) increased with increasing N rate in 2005, but the quantity of medium size onions ($P = 0.02$) decreased with increasing N rate when averaged over irrigation systems (Table 1). The N rate × irrigation system interactions were not significant ($P > 0.5$) in both years. Nitrogen fertilization had no effect on onion size in 2006 (Table 1).

The drip system had more colossal and jumbo size onions than the furrow system in 2005 and 2006, and generally fewer medium size onions than the furrow system when averaged over N rates (Table 2). The higher established plant population in 2006 (310,763 plants ha^{-1}) vs. the lower population in 2005 (263,423 plants ha^{-1}) may have reduced the colossal size onion yield in 2006 due to closer plant spacing. In 2005, the percentage of colossal size onions increased from 5% for the check plot (no N added) to a maximum of 14% of the total marketable onions at the 134 kg N ha^{-1} rate ($P = 0.08$) when averaged over irrigation systems. Increasing N rate did not change the percentage of jumbo size onion as a percentage of the total marketable onion yield, averaging 80% over all N rates and irrigation systems in 2005. Increasing N rate decreased the percentage of medium sized onions from 14.4% at the lowest N rate to 5.4% at the highest N rate ($P = 0.01$) when averaged over irrigation systems in 2005. This demonstrates the need to have adequate N available to maximize bulb size. These results also demonstrate the value of the drip system in producing larger size onions with more market value compared to the furrow irrigation system.

An adjusted gross dollar return per hectare (gross return *minus* N fertilizer, water, and drip system costs) was calculated for each treatment. Adjusted gross returns (Fig. 2) were increased with

Table 1. Colossal, jumbo, and medium sized and total marketable fresh onion yield as a function of N rate each year averaged over irrigation systems.

	Fresh onion market size class and total marketable yield†							
	2005				2006			
N rate	Colossal	Jumbo	Medium	Total	Colossal	Jumbo	Medium	Total
kg N ha^{-1}	Mg ha^{-1}							
0	5.07c	67.13c	11.26a	83.46b	0.82a	51.40a	26.03a	77.52a
45	6.16bc	70.31bc	8.43abc	84.90b	0.62a	57.32a	21.77a	79.18a
90	11.20ab	74.27abc	8.80ab	94.27a	0.00a	55.01a	21.33a	76.42a
134	14.22a	77.64a	7.05bc	98.91a	0.85a	52.77a	25.96a	78.82a
179	13.74a	76.87a	6.17bc	96.78a	0.64a	59.46a	21.00a	80.54a
224	14.11a	78.74a	5.25c	98.10a	0.31a	59.53a	22.53a	82.16a
$P > F$	0.12	0.02	0.02	0.01	0.66	0.59	0.43	0.66
α	0.20	0.05	0.05	0.05	NS	NS	NS	NS

† Yield values within a column followed by the same letter are not significantly different at α shown.

Table 2. Colossal, jumbo, and medium-sized fresh onion yields as a function of irrigation system each year averaged over N rate.

Irrigation system	Year	Colossal†	Jumbo†	Medium†
		Mg ha^{-1}		
Drip	2005	12.48a	78.59a	7.26a
Furrow	2005	9.02b	69.73b	8.39a
Drip	2006	1.00a	67.60a	17.86b
Furrow	2006	0.09b	44.22b	28.35a

† Yield values within a year and size class followed by the same letter are not significantly different at α = 0.05.

Table 3. Onion leaf and bulb yields (oven dry) and N accumulation as a function of sample harvest date and irrigation system (significant irrigation system × harvest date interaction) averaged over N rates and years.†

Sample date	Yield		N accumulation	
	Drip	Furrow	Drip	Furrow
	kg dm ha^{-1}		kg N ha^{-1}	
Onion leaves				
24 May	44	42	1.4	1.4
7 June	195	226	6.8	8.1
21 June	708	691	20.9	20.0
5 July	1685	1653	40.7	37.3
20 July	3049	2532	66.8	51.0
2 August	2784	2648	52.9	49.5
16 August	2643	2198	47.0	35.8
30 August	2016	1688	25.7	21.2
LSD (0.05)	139 WIS		3.0 WIS	
	159 BIS		3.3 BIS	
Onion bulbs				
24 May	7	6	0.2	0.2
7 June	24	28	0.8	1.0
21 June	118	131	2.9	3.0
5 July	531	649	7.7	7.8
20 July	1933	2055	25.6	25.2
2 August	4808	4699	51.1	49.5
16 August	7504	6699	84.4	73.6
30 August	7685	6626	105.2	89.7
LSD (0.05)	232 WIS		2.9 WIS	
	247 BIS		2.8 BIS	
Onion leaves + bulbs				
24 May	51	48	1.6	1.6
7 June	218	253	7.6	9.0
21 June	826	822	23.7	23.0
5 July	2215	2303	48.5	45.1
20 July	4981	4587	92.4	76.2
2 August	7592	7347	104.1	99.0
16 August	10146	8897	131.4	109.5
30 August	9701	8314	130.9	110.9
LSD (0.05)	306 WIS		4.7 WIS	
	347 BIS		5.1 BIS	

† BIS, between irrigation systems; dm, dry matter; WIS, within irrigation system.

Table 4. Oven dry onion bulb yield as a function of N rate and sample harvest date (significant N rate by harvest date interaction) averaged over irrigation systems and years, and N rate and years (significant N rate × year interaction) averaged over irrigation system and harvest dates.

	Fertilizer N rate, kg N ha^{-1}					
	0	45	90	134	179	224
Sample date	Onion bulb yield					
	kg ha^{-1}					
24 May	7	6	7	8	6	7
7 June	22	28	28	28	22	28
21 June	101	135	125	128	126	131
5 July	558	602	570	607	577	625
20 July	1533	2014	2069	2305	1994	2048
2 August	4140	4443	5201	5070	4687	4981
16 August	6764	7322	7008	6946	7297	7271
30 August	6793	6865	7100	7403	7282	7492
LSD (0.05)	402 within N rate; 416 among N rates					
Year						
2005	2320	2660	2895	2878	2893	2984
2006	2659	2694	2632	2746	2605	2662
LSD (0.05)	259 within N rate; 265 among N rates					

increasing N rate in 2005 for both irrigation systems with no significant N rate by irrigation system interaction (P = 0.21). Adjusted gross returns were significantly greater with the drip system (\$32,985 ha^{-1}) than with the furrow system (\$30,328 ha^{-1}) when averaged over N rates in 2005. Adjusted gross returns were significantly greater with the drip system (\$40,777 ha^{-1}) than with the furrow system (\$33,285 ha^{-1}) when averaged over N rates in 2006. Adjusted gross returns were significantly greater with the drip system (\$36,881 ha^{-1}) than with the furrow system (\$31,807 ha^{-1}) when averaged over N rates and years. A significant irrigation system by year interaction resulted from the drip irrigation having a greater adjusted gross return than furrow irrigation; however, the difference was greater in 2006 (\$7,492 ha^{-1}) than in 2005 (\$2,657 ha^{-1}).

Onion Yield–Dry Weight

Onion leaf biomass (oven dry basis) averaged over irrigation systems and years did not vary significantly with N rate, nor were the N rate × irrigation system and N rate × year interactions significant. Onion leaf biomass was significantly greater in 2005 (1669 kg ha^{-1}) than in 2006 (1431 kg ha^{-1}) when averaged over N rates, irrigation systems, and harvest dates. Leaf biomass varied with irrigation system and harvest date (Table 3), with a significant irrigation system by harvest date interaction. Onion leaf development started increasing rapidly in mid-June, then leveled off in late July and decreased slightly during August as older leaves began to senesce and drop off within both irrigation systems. The interaction occurred because leaf biomass was similar between irrigation systems in May, June, and early July, but the drip system attained greater leaf yields than the furrow system during the latter part of the growing season (Table 3). The dry matter accumulations observed in 2005 and 2006 are similar to the onion growth curves reported by Schwartz and Bartolo (1995) and Halvorson et al. (2002).

Onion bulb yields were influenced by irrigation system and harvest date as shown in Table 3. The irrigation system by harvest date interaction resulted from both irrigation systems having similar yields from May through early August, then the drip system having greater yields from mid-August to harvest (Table 3). During May, June, and July there was no difference in bulb yield between irrigation systems, however in August, bulb yield was greater with the drip than furrow irrigation system. Onion bulb initiation began in early June both years. Onion bulb development was very slow until early July, then developing very rapidly until maturity in late August. Onion bulb yields (oven dry basis) varied significantly with N rate when averaged over irrigation systems and years, with a significant N rate × year interaction (Table 4). The interaction occurred due to a greater bulb response to N fertilization in 2005 than in 2006, similar to the fresh bulb yield. A significant N rate by harvest date (Table 4) interaction was also present for onion bulb dry weight yields. There were no differences in dry matter bulb yields among N rates until the first sampling date in August. The higher N rates began achieving greater dry matter yields than the lower N rates starting in mid-August. Bulb dry matter yields were near maximum with the application of 90 kg N ha^{-1} at the 30 August harvest date in 2005, with no significant differences between N rates in 2006.

Nitrogen Uptake

Nitrogen accumulation by the onion leaves averaged over irrigation system, years, and harvest date was increased by N fertilization with the 224 kg ha^{-1} N rate having significantly higher N accumulation (32.1 kg N ha^{-1}) than the 0 and 45 kg ha^{-1} N rates (27.6 and 29.4 kg N ha^{-1}, respectively). The significant ($P = 0.069$) N rate by harvest date interaction is shown in Table 5. During May and early June, N fertilization rate had little influence on the N accumulation by onion leaves. Starting in late June through July, the higher N rates (>45 kg N ha^{-1}) had the greatest amount of leaf N accumulation. In August, N levels in the onion leaves declined until harvest, with no significant differences in N accumulation with N rate. The N accumulated by the onion leaves was apparently being translocated to the onion bulbs. Irrigation system significantly influenced N accumulation by onion leaves, with the drip system having significantly more N accumulated (32.8 kg N ha^{-1}) than the furrow system (28.0 kg N ha^{-1}) when averaged over N rates, years, and harvest dates. The N rate by irrigation system interaction was not significant. The significant irrigation system by harvest date interaction for leaf N accumulation is shown in Table 3. During May and June, there were no significant differences in leaf N accumulation between irrigation systems; however, leaf N accumulation was greater for the drip system than the furrow system from July through final harvest. In both irrigation systems, N uptake increased from May through July, then declined until harvest. Nitrogen accumulation by onion leaves was significantly greater in 2005 (32.2 kg N ha^{-1}) than in 2006 (28.6 kg N ha^{-1}) when averaged over all variables. This reflects the greater fresh onion yield in 2005 than in 2006. The N accumulation patterns for onion leaves reported for this study are similar to the N accumulation patterns reported by Halvorson et al. (2002). At final harvest, N accumulation in the leaves was significantly greater with the drip system (25.7 kg N ha^{-1}) than with the furrow system (21.2 kg N ha^{-1}). The C to N ratio of the onion leaves returned to the soil at harvest was 31 when averaged over years.

Nitrogen accumulation by the onion bulbs increased with increasing N rate, with a significant N rate by harvest date interaction (Table 5). During May, June, and early July, N rate had no affect on the N accumulation by onion bulbs. From mid-July through harvest, N accumulation in the onion bulbs increased with increasing N rates with N accumulation leveling off above the 134 kg ha^{-1} N rate. Nitrogen accumulation increased in the onion bulbs with each sequential harvest date. At final harvest, N accumulation in the bulbs was greater with the drip system (105.2 kg N ha^{-1}) than with the furrow system (89.7 kg N ha^{-1}) when averaged over N rates and years (Table 3).

The significant irrigation system by harvest date interaction is shown in Table 3 for onion bulb N accumulation. From May through early August, there were no significant differences in N accumulation by the onion bulbs between irrigation systems; however, at the 16 and 30 August sampling dates, the drip system had greater N accumulation by onion bulbs than the furrow system. The N rate × irrigation system interaction was not significant for onion bulb N accumulation. In contrast to onion leaves, N uptake by onion bulbs was greater in 2006 (35.3 kg N ha^{-1}) than in 2005 (31.2 kg N ha^{-1}), with significant N rate × year and irrigation system × year interactions. The significant N rate × year interaction occurred as a result of greater N accumulation by onion bulbs in 2006 than in 2005 at the lower N rates with similar N accumulation levels at the higher N rates (data not shown). The significant irrigation × year interaction resulted from a larger difference in onion bulb N accumulation (data not shown) between the drip and furrow systems in 2005 (drip 21% greater than furrow) than in 2006 (drip 3% greater than furrow).

Table 5. Onion leaf and bulb N accumulation as a function of N rate and sample harvest date averaged over irrigation systems and years (significant N rate × harvest date interaction).

	Fertilizer N rate, kg N ha^{-1}					
	0	45	90	134	179	224
Sample date	N accumulation					
	kg N ha^{-1}					
Onion leaves						
24 May	1.2	1.3	1.3	1.5	1.6	1.5
7 June	6.2	7.5	7.7	7.7	7.3	8.1
21 June	15.4	20.0	20.3	20.7	23.1	23.0
5 July	30.5	37.7	40.5	42.7	40.0	42.7
20 July	53.4	53.7	63.8	60.6	59.2	62.4
2 August	49.8	49.3	51.7	51.2	50.2	55.2
16 August	40.0	43.3	41.3	39.9	43.7	40.1
30 August	24.2	22.7	24.6	22.9	22.4	23.8
LSD (0.10)	4.4 within N rate; 4.7 among N rates					
Onion bulb						
24 May	0.1	0.1	0.2	0.2	0.2	0.2
7 June	0.7	1.0	1.0	0.9	0.8	1.0
21 June	2.1	2.9	3.0	3.1	3.3	3.3
5 July	6.0	7.6	8.0	8.0	8.2	8.7
20 July	18.3	24.1	27.7	28.1	26.6	27.6
2 August	41.7	45.3	55.3	55.4	50.8	53.4
16 August	71.9	79.0	74.5	80.7	82.3	85.7
30 August	88.3	88.2	93.0	105.7	103.3	106.2
LSD (0.05)	5.0 within N rate; 5.1 among N rates					
Onion leaves + bulbs						
22 May	1.3	1.5	1.5	1.7	1.7	1.7
7 June	6.9	8.5	8.7	8.6	8.1	9.0
21 June	17.5	22.9	23.4	23.8	26.4	26.3
5 July	36.5	45.3	48.5	50.7	48.2	51.3
19 July	71.7	77.8	91.5	88.8	85.8	90.0
2 August	91.5	94.5	107.0	106.6	101.0	108.6
16 August	111.9	122.3	115.8	120.7	126.1	125.9
30 August	112.5	110.9	117.6	128.6	125.7	130.0
LSD (0.05)	8.2 within N rate; 8.8 among N rates					

Total N accumulation (leaves + bulbs) varied significantly with N rate, irrigation system, and harvest date when averaged over years with significant N rate × harvest date (Table 5) and irrigation system × harvest date interactions (Table 3). The irrigation system × harvest date interaction resulted from no differences in total N accumulation from May through early July, then greater total N accumulation with the drip system than with the furrow system until harvest (Table 3). The N rate × harvest date interaction resulted from little difference in total N accumulation among N rates in May and June, with the higher N rates tending to have greater N accumulation than the 0 and 45 kg ha^{-1} N rates during mid-July until harvest (Table 5). A N rate × year interaction occurred due to lower total N accumulation at the low N rates in 2005 than in 2006, but greater N accumulation in 2005 than in 2006 at the two highest N rates (data not shown). This reflects the greater response of onion to N application in 2005 than in 2006. The greater N response in 2005 probably reflects a lower level of mineralizable soil N in the 2005 plots due to the previous 4 yr of corn and 1 yr of chile pepper production with conservative N application rates compared to the 2006 onion plots where soybean was grown the previous year and relatively high rates of N application to previous crops. A significant irrigation × year interaction resulted from a larger difference in total N accumulation (data not shown) between the drip and furrow systems

Table 6. Soil NO_3–N levels in the 0- to 60-cm and 0- to 180-cm depths before onion planting in the spring, after onion harvest in the fall, and before planting a corn crop in April of 2006 or 2007 following onion in rotation.

	Soil NO_3–N					
	Before planting		After harvest		April of next year	
N rate	0– 60 cm	0–180 cm	0–60 cm	0–180 cm	0–60 cm	0–180 cm
kg N ha^{-1}	kg N ha^{-1}					
	February 2005		September 2005		April 2006	
0	45c†	80bc‡	41c	93c	72c	107e
45	48c	79c	72bc	140bc	109bc	159de
90	56bc	87bc	70bc	132c	145b	213cd
134	56bc	74c	114ab	223ab	159b	231bc
179	69b	111ab	141a	249a	250a	329a
224	91a	125a	87abc	180abc	215a	289ab
	February 2006		September 2006		April 2007	
0	52a	77a	25c	50c	48c	94c
45	58a	81a	41c	70c	51bc	119bc
90	58a	79a	77bc	126bc	73ab	169b
134	55a	78a	82bc	125bc	75a	173b
179	53a	76a	133ab	204ab	77a	167b
224	47a	67a	212a	286a	81a	233a
Irrigation	February 2005		September 2005		April 2006	
Drip	56b	84b	96a	211a	200a	293a
Furrow	66a	101a	79a	128b	117b	150b
	February 2006		September 2006		April 2007	
Drip	56a	79a	92a	137a	71a	178a‡
Furrow	52a	74a	99a	150a	64a	140b

† Soil NO_3–N values within a sampling depth for each year followed by the same letter are not significant at α = 0.05 unless otherwise indicated.

‡ Soil NO_3–N values within the 0- to180-cm depth for February 2005 followed by the same letter are not significant at α = 0.10.

in 2005 (drip 21% greater than furrow) than in 2006 (drip 8% greater than furrow). At final harvest, total N accumulation (leaves + bulbs) was significantly greater with the drip system (130.9 kg N ha^{-1}) than with the furrow system (110.9 kg N ha^{-1}) when averaged over N rates and years.

Irrigation Water Use Efficiency

The IWUE based on gross water applied was not affected by N fertilization when averaged over irrigation systems and years. The IWUE was significantly greater for the drip system (1216 kg yield cm^{-1} H_2O) than for the furrow irrigation system (534 kg yield cm^{-1} H_2O) when averaged over N rates and years. The IWUE was greater for 2005 (993 kg yield cm^{-1} H_2O) than for 2006 (757 kg yield cm^{-1} H_2O) when averaged over N and irrigation treatments. The only interaction that was significant was the irrigation × year interaction. This resulted from IWUE being greater in 2005 (1441 kg yield cm^{-1} H_2O) than in 2006 (990 kg yield cm^{-1} H_2O) for the drip irrigation system and not significantly different between years for the furrow irrigation system (545 kg yield cm^{-1} H_2O in 2005 and 524 kg yield cm^{-1} H_2O in 2006).

Nitrogen Use Efficiency

Nitrogen use efficiency (NUE_1) decreased significantly with increasing N rate when expressed as a function of total N uptake and AN. A significant N rate × year interaction was present with NUE_1's of 238, 98, 80, 59, 45, and 47% in 2005 and 154, 90, 62, 54, 45, and 39% in 2006 for the 0, 45, 90, 134, 179, and 224 kg ha^{-1} N rates, respectively. The interaction resulted from greater NUE_1 differences between years at the lower N rates than at the higher N rates. This probably reflects a lower level of mineralizable N in the lower N rate plots of the 2005 study compared to a potentially higher level of readily available mineralizable N following soybean in the 2006 study. The high NUE_1 values for the zero N rates suggest that mineralizable N became available to the onion crop during the growing season and was not accounted for in the AN value used to calculate NUE_1. A reliable mineralizable N value was not available to use in this calculation. The drip irrigation system resulted in a greater NUE_1 (92%) than for the furrow irrigation system (76%) when averaged over N rates and years. Average NUE_1 was greater in 2005 (94%) than in 2006 (74%) due to a greater total N uptake with the higher onion yield in 2005.

The NFUE for the 2006 onion crop (4.1%) was not significantly affected by N fertilization rate ($P = 0.81$), but was significantly different between irrigation systems ($P = 0.02$). In 2006, NFUE was 7.1% for drip and 1.0% for furrow irrigation systems. These NFUE values are lower that the NFUE values of 30% reported by Sammis (1997) and 15% by Halvorson et al. (2002). This demonstrates the N management concern when growing irrigated onions which are very shallow rooted, yet require considerable N application to attain high yield and large size onions.

Expressing NUE_2 on a fresh yield basis as a function of AN, NUE_2 decreased with increasing N rate with a significant N rate × year interaction. NUE_2's were 1637, 717, 560, 409, 312, and 306 kg yield kg^{-1} AN in 2005 and 1199, 693, 473, 395, 332, and 290 kg yield kg^{-1} AN in 2006 for the 0, 45, 90, 134, 179, and 224 kg ha^{-1} N rates, respectively. The interaction resulted from greater NUE_2 differences between years at the lower N rates than at the higher N rates. The drip irrigation system resulted in a greater NUE_2 (654 kg yield kg^{-1} AN) than with the furrow irrigation system (566 kg yield kg^{-1} AN). Average NUE_2 was greater in 2005 (657 kg yield kg^{-1} AN) than in 2006 (564 kg yield kg^{-1} AN) as a result of the greater onion yield in 2005.

Residual Soil Nitrate-Nitrogen

Residual soil NO_3–N levels at study initiation, after onion harvest, and before planting a corn crop the following year are reported in Table 6. Initial soil NO_3–N levels in the 0- to 60-cm soil depth were slightly higher in the furrow plots than the drip irrigation plots in 2005, but similar in 2006. After onion harvest, residual soil NO_3–N levels were not different between irrigation systems in the 0- to 60-cm soil depth both years. In 2005, residual soil NO_3–N levels were significantly greater with the drip system than with the furrow system in the 0- to 180-cm soil depth, reflecting less water lost to deep percolation with drip (11 cm) compared with furrow (104 cm). In April 2006, residual soil NO_3–N levels were significantly greater in the plots of the 2005 drip system than in the 2005 furrow system plots. For the 2006 onion crop, there was no significant difference in residual soil NO_3–N levels between the drip and furrow systems at planting or after harvest in the 0- to 180-cm soil depth; however, residual soil NO_3–N levels were slightly greater in the drip than furrow irrigation plots in April 2007, reflecting the loss of 88 cm of irrigation water to deep percolation with the furrow system compared to 36 cm for the drip system. Residual soil NO_3–N levels were greater following the onion crop in 2005 than in 2006, particularly with the drip system. More rainfall during the latter part of the growing season in 2006 plus a greater loss of irrigation water with drip irrigation in 2006 than in 2005 may have resulted in more leaching of the N applied to the onion crop than occurred with the drier growing season in 2005. Residual

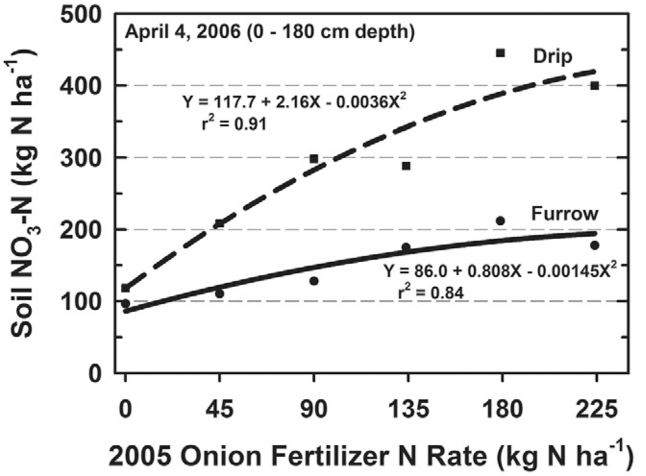

Fig. 3. Residual soil NO_3–N levels in the spring of 2006, following the 2005 onion crop, as a function of the 2005 fertilizer N rate and irrigation system (significant N rate × irrigation system interaction).

soil NO_3–N generally increased with increasing N rate in both systems with no significant N rate × irrigation system interaction, except for the 0- to 180-cm soil depth in April of 2006 following the 2005 onion crop (Fig. 3). The data in Fig. 3 suggest that the drip system reduced soil NO_3–N leaching compared with the furrow system in 2005.

SUMMARY

This study demonstrates that potential economic returns can be maintained or improved by using the lower water requirement, but more costly drip irrigation system for onion production rather than the normal furrow irrigation production system. Fresh onion yield response to N fertilization was similar for both irrigation systems in 2005, with no significant response to N fertilization in 2006. Onion yields were near maximum with the application of 132 kg N ha^{-1} in 2005. Nitrogen fertilization increased onion size in 2005. Onion response to N fertilization was significant following chile pepper but not following soybean in rotation. The results suggest that onion producers can take a conservative approach to N application on onion in the Arkansas River Valley area of Colorado unless the amount of potentially mineralizable N in the soil profile has been reduced by previous crops, such as several years of continuous corn, before onion production. The drip system produced greater onion yields with more large sized onions, greater estimated economic returns, and used 64% less irrigation water than with the furrow irrigation system averaged over 2 yr. The drip irrigation resulted in greater IWUE, NFUE, and NUE than with furrow irrigation. Less NO_3–N appears to have been lost from the soil 0- to 180-cm profile with the drip system compared with the furrow irrigation system. Visually, soil erosion was also less with the drip system than with the furrow irrigation system. Converting from furrow irrigation to drip irrigation for onion production appears to have economical and environmental advantages in the Arkansas River Valley of Colorado.

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